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Incorporation of a Redfern Integrated Optics ORION Laser Module with an IPG Photonics Erbium Fiber Laser to Create a Frequency-Conversion Photon Doppler Velocimeter for US Army Research Laboratory Measurements: Hardware, Data Analysis, and Error Quantification

Michael B Zellner and Brian E Schuster

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14. ABSTRACT

This report addresses benefits and difficulties of integrating a Redfern Integrated Optics ORION laser module with an IPG Photonics Erbium fiber laser to create a frequency-conversion photon Doppler velocimeter. Many of the implications arise from the use of 2 independent laser sources to create the optical beat frequencies measured by the heterodyne system and the associated drift of their center frequencies. This drift was quantified and analysis techniques were developed to actively monitor the drift, in situ, during dynamic measurements. Finally, an example of postprocessing analysis is given, which quantifies the applicable error from using such a system to the overall measurement.

15. SUBJECT TERMS

photon Doppler velocimetry, laser, beat frequency, heterodyne velocimetry, frequency conversion

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1. Introduction

Frequency-conversion photon Doppler velocimetry (FCPDV)[1,2] varies from conventional photon Doppler velocimetry (PDV)[3,4] in that it uses a slightly modulated reference frequency to shift the Doppler signal away from the baseline. This technique was developed to provide significant benefit in shock compression experiments, allowing for resolution of low-velocity transients signals that were incapable of being resolved with conventional techniques. Utilization of the FCPDV method, however, can also provide other benefits over the conventional fielded PDV technique. Because the frequency-conversion method can artificially shift the beat frequency toward a positive or negative direction, one could optically down-shift the typical measured frequencies, allowing for measurements of very fast events using more cost-effective detectors (oscilloscopes) of lower bandwidth. If one wants to resolve directionality of an oscillating surface, one could optically shift the reference frequency away from the baseline to eliminate the directionality ambiguity that occurs with PDV when paired with a Fourier analysis suite such as SIRHEN. This ambiguity ultimately arises from optoelectronic detectors relating the absolute value of the Doppler shifted beat frequency. The resolve of directionality is achieved by providing a sufficient buffer such that the frequency of the Doppler shifted beat signal does not extend beyond the offset instilled by use of the reference laser (a positive or negative buffer could be instituted). These types of measurements are particularly useful to US Army Research Laboratory applications that use photon Doppler velocimetry systems for significantly broader uses than shock-compression characterization.[5–7]

This report addresses the benefits and difficulties of integrating a Redfern Integrated Optics (RIO) ORION laser module with an IPG Photonics Erbium Fiber Laser to create an FCPDV, and the system's applicability to making measurements as described previously. Many of the implications arise from the use of 2 independent laser sources to create the optical beat frequencies measured by the heterodyne system. Although the main laser uses a RIO ORION laser module as its seed, the individuality between the IPG Photonics laser and the PDV reference RIO ORION laser produces center frequency drifts at differing rates. These drifts cause a modulation of the beat frequency that is a function of the drift rate of the RIO ORION seed within the IPG Photonics main laser and the drift rate of the RIO ORION PDV reference laser. In this report, the drift of both lasers was quantified, and analysis techniques were developed to actively monitor the drift, in situ, during dynamic measurements that use both lasers. Finally, an example of postprocessing analysis is given, which quantifies the applicable error from using such a system to the overall measurement.

## 2.	Results and Discussion

The main laser in the PDV system tested is a 2-W, continuous wave, single frequency, Erbium doped IPG Photonics fiber laser (model no.: ELR-2-1550-LP-SF) that uses a RIO ORION laser module as its seed. This system is turnkey and uses a defined peak wavelength preset by the manufacturer. The PDV reference laser RIO ORION is a 10-mW, continuous wave, diode pumped external cavity laser (part no.: RIO0075-3-1-3-AV6). It uses a user-controlled thermoelectric cooler (TEC) to adjust the temperature of the cavity allowing the user to adjust its center wavelength. Figure 1 shows measurements of the laser central wavelengths from both the IPG Photonics (black) and RIO ORION PDV reference module (blue) when tuned to a wavelength approximately 0.03 nm greater than the IPG Photonics center wavelength. The measurements were made using a Bristol Instruments 771 optical spectrum analyzer using its wavelength measuring mode. The instrument was operated in high-resolution (2 GHz) mode, spanning wavelengths from 520 to 1700 nm. The wavelength measuring feature of this spectrum analyzer references an internal helium-neon laser to measure the peak wavelength of an incoming signal to within ±0.2 ppm (±0.0002 nm at 1000 nm). For stability, both lasers and the optical spectrum analyzer were fully powered up and emitting for 10 min prior to measurements.
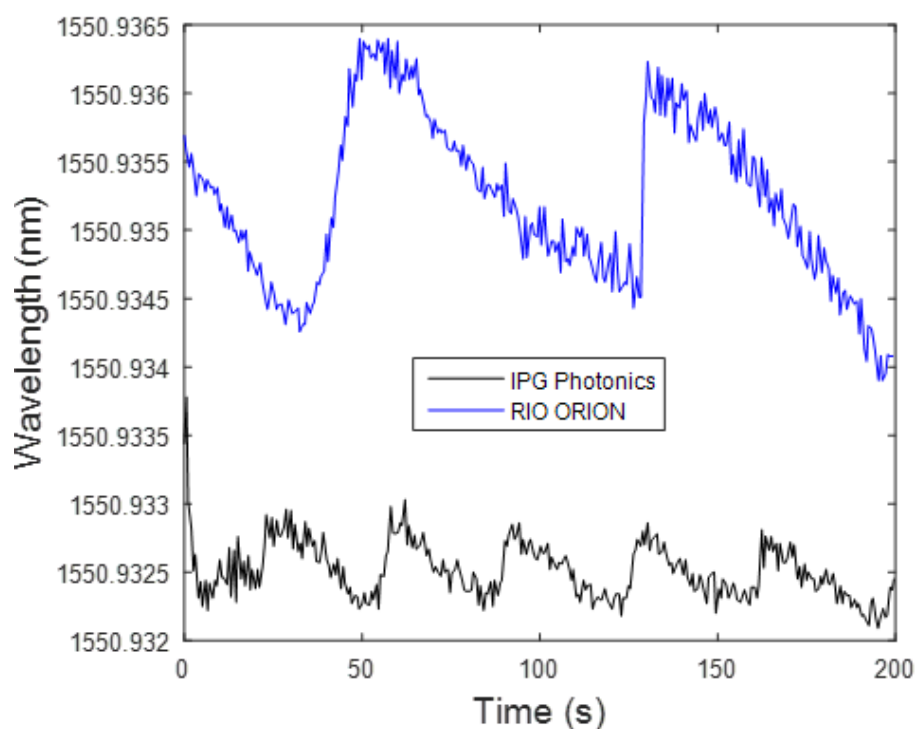
**Fig. 1	Measurements of the IPG Photonics' (black) and RIO ORION module's (blue) central wavelengths as functions of time**

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Figure 1 demonstrates how the 2 lasers' central wavelengths drift from thermal effects and the resulting structure imposed by internal controls used to stabilize the central wavelength from thermal response. This control produces a sawtooth fluctuation of the peak wavelength as a function of time. The control loop for the IPG Photonics laser appears to have a higher refresh frequency resulting in less peak-to-peak wavelength drift than the RIO ORION PDV reference laser. The short-term drift of both lasers occurs near a rate of 0.025 pm/s. The RIO ORION, however, appears to have a significantly larger long-term drift. When applying a linear fit to both data sets, the IPG Photonics laser shows a long-term decrease in wavelength of 0.00133 pm/s while the RIO ORION shows a long-term decrease in wavelength of 0.00203 pm/s. A combination of the differences in refresh time and the long-term rates eliminates the ability to precisely define the PDV main and reference frequencies, and therefore the PDV beat frequency, prior to an experiment. Using the data displayed in Fig. 1 as an example, one would expect to see velocity shifts within the PDV spectrum to range from 435 m/s when using peak values to 116 m/s when using valley values.[3]

Although PDV measurements typically occur over relatively short timescales (on the order of microseconds), measurements made over longer periods could incur influence from dynamic modulation of the beat frequency. For this reason, and because we cannot predetermine the wavelength difference, it becomes necessary to measure the beat frequency of the RIO ORION PDV reference laser and the IPG Photonics PDV main laser, in situ, during the PDV measurements. To make such measurement, one can take advantage of the fact that all fiber optic junctions produce some amount of back reflection. If the amount of back reflected light from junctions along the fiber optic path of the main PDV laser (the IPG Photonics laser) is sufficient, one could balance the amount of injected reference light to actively measure the beat frequency between the reference source and the IPG Photonics source (from the nonmoving joint back reflections), and the beat frequency between the reference source and the Doppler shifted light from the moving sample surface.

To demonstrate the technique, and to demonstrate the overall applicability of an FCPDV toward making measurements of an oscillating surface, the velocity of a speaker cone oscillating at 100 Hz was measured using a conventional PDV and an FCPDV system. Figure 2 shows the geometry of the experiments. Figure 3 shows a spectrogram produced when our conventional PDV system measures the velocity of a speaker cone oscillating at 100 Hz. The data of interest appear as increasing and decreasing velocity varying between 0 and 0.16 m/s.* At first glance, these data appear to relate a period of approximately 0.005 s, which does not correlate with

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*The constant velocity features near 0.2 and 0.4 m/s are electronic artefacts of the detectors used.

the expected period of 0.01 s for a 100-Hz oscillating speaker cone. In reality, 2 of the 0.005-s cycles corresponds to a single speaker cone oscillation; one cycle relates the motion of the speaker when its displacement is toward the PDV probe and in front of its equilibrium position, and the second cycle relates the motion of the speaker when its displacement is away from the PDV probe and beyond its equilibrium position. These data demonstrate how conventional PDV, when analyzed with a Fourier method, is incapable of discerning velocity directionality when the measured beat frequency surpasses both the upper and lower frequencies of the PDV system (which are identical in this case, as the system uses a tap-coupler to extract 1% of its own light for use as the reference leg). Here, one would have to add additional information to discern directionality, as it is known that in reality the speaker cone moves toward and then away from the PDV probe in a roughly sinusoidal manner.


Fig. 2   Schematic of the experimental setup used to demonstrate directionality effects of PDV measurements
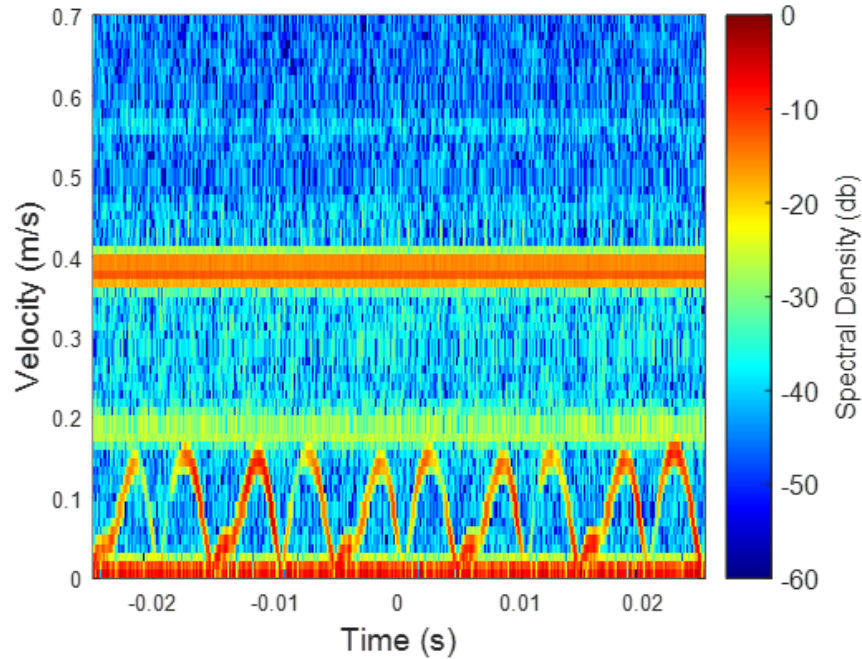
Fig. 3 **Spectrogram produced when a conventional PDV system measures the velocity of a speaker cone when oscillating at 100 Hz**

Figure 4 shows a spectrogram produced when our FCPDV (composed of an IPG Photonics main laser and a RIO ORION reference laser) measures a stationary, nonoscillating speaker cone. To assess the effects associated with the thermal drift of the 2 lasers, and their deviation from an idealized singular frequency reference beat, we first extract a velocity versus time profile from the spectrogram. We do this by fitting the velocity at each time step using a Gaussian function. We can then compute how the profile evolves in time. Table 1 summarizes numerous parameters that characterize the profile evolution. It was found that the signal produced a velocity profile with a 0.02-m/s standard deviation and peak accelerations on the order of 227 m/s^2 (i.e., this would impart a 0.227-m/s error on a 1-ms duration experiment).
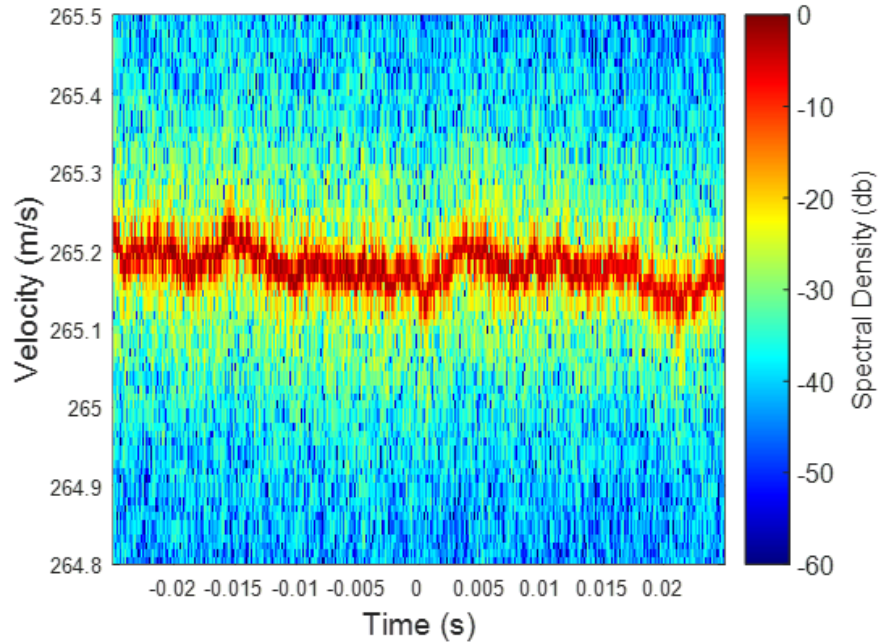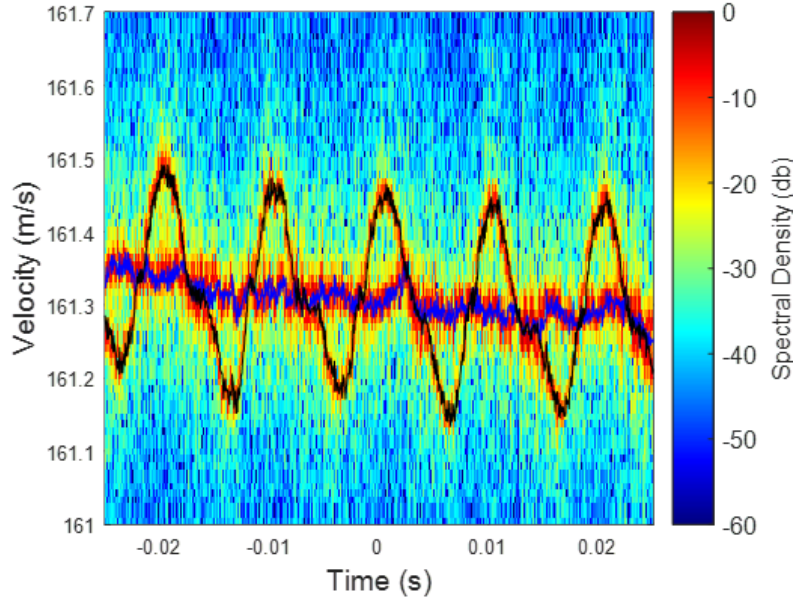
Fig. 4 **Spectrogram produced when our FCPDV (composed of an IPG Photonics main laser and a RIO ORION reference laser) measures a stationary, nonoscillating speaker cone**

Table 1 **Numerous parameters that characterize the velocity and acceleration profiles when PDV measurements using a dual-laser system were acquired from a nonoscillating speaker**

Mean velocity (m/s)	Maximum velocity (m/s)	Minimum velocity (m/s)	Standard deviation of mean velocity (m/s)	Mean acceleration (m/s²)	Maximum acceleration (m/s²)	Standard deviation of acceleration (m/s²)
265.1754	265.2290	265.1151	0.0200	–0.7591	227.6298	32.4346

Figure 5 shows a spectrogram produced when our FCPDV system measures the velocity of a speaker cone when oscillating at 100 Hz. To become capable of measuring both the velocity computed from the beat frequency of the reference laser and the Doppler shifted light reflected off of the moving speaker cone, and the velocity computed from the beat frequency of the reference laser and the back-reflected light of the main laser from a nonmoving fiber optic junction, the amount of light injected from the reference laser was balanced to the sum of the light reflected from a junction and the light expected to be returned from the sample. To do this the following steps were performed.

Fig. 5 **Spectrogram produced when our FCPDV system measures the velocity of a speaker cone when oscillating at 100 Hz. Overlaid on the spectrogram are the following: a black fit to the velocity computed from the beat frequency of the reference laser and the Doppler shifted light reflected off of the moving speaker cone, and a blue fit to the velocity computed from the beat frequency of the reference laser and the back-reflected light of the main laser from a nonmoving fiber optic junction.**

1) After all fiber optic junctions were connected, and all internal voltage-driven-attenuators were minimized to allow full transmission of light within the PDV system, the main PDV laser was emitted while the probe was pointed into space so no reflected light would be returned into the circulator via the probe path. The internal power meter was used to note the total returned power ($P_{baseline}$).

2) While the main PDV laser was emitting, the PDV probe was aimed at the target specimen. The internal power meter was used to measure the total returned power from the sample reflection (P_{sample}). The voltage-driven attenuator can be used to reduce the power if too intense.

3) While the main PDV laser was emitting, the probe was pointed into space so no reflected light would be returned into the circulator via the probe path, and a junction along the probe path was loosened until the power meter indicated $P_{back\ reflection} = P_{sample} - P_{baseline}$.

4) While the main PDV laser was emitting, the PDV probe was re-aimed at the target specimen. The internal power meter was used to measure the total returned power to ensure that the total returned power ($P_{sample} + P_{back\ refelction}$) was approximately twice that from the sample reflection ($2 \times P_{sample}$).

5) Sufficient reference light was injected into the system to maximize the amplitude of the measured beat frequencies.

The resulting spectrogram produced evenly powered spectral density features characterizing both the PDV laser beat frequency and the dynamic frequency. Black and blue Gaussian-based fits were overlaid on the spectrogram representing the velocities, respectively.

Figure 6 shows the corrected velocity history of the speaker cone vibrating at 100 Hz as measured by an FCPDV. To correct the signal, one simply needs to subtract the dynamic baseline from the measured signal at every time step (i.e., the blue and black velocity histories displayed in Fig. 5). In this measurement, the speaker directional ambiguity has been resolved and it now oscillates with steady amplitude at 100-Hz frequency. Figure 7 shows a comparison of the corrected FCPDV to the velocity history as measured by a conventional PDV in its raw and user-defined directionality forms (informed from the FCPDV data). For ease of comparison, a –0.0022-s shift was applied to the PDV data so that the peaks and valleys aligned. These data show good agreement in magnitudes and timing. Deviations between the negative velocity onsets (indicated by green ellipse in Fig. 7) relate to the quality of the fit extracted from the spectrograms of both traces. This could be improved with additional postprocessing but was deemed unnecessary for this example.
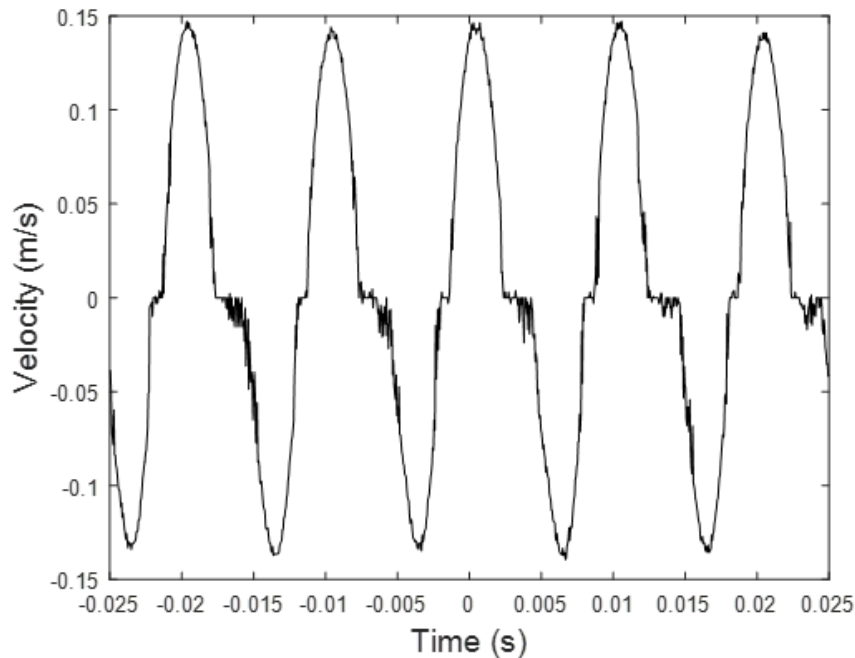
Fig. 6   Corrected velocity history of the speaker cone vibrating at 100 Hz as measured by an FCPDV
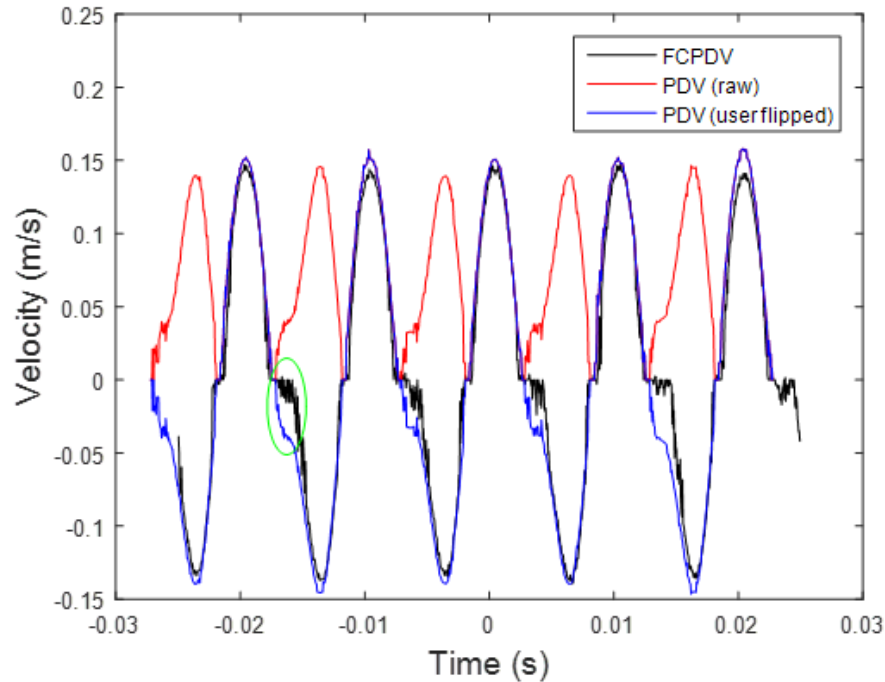
Fig. 7   Comparison of extracted fits from FCPDV and PDV measurements of a speaker oscillating at 100 Hz

3.   Conclusions

This report addresses benefits and difficulties of integrating a Redfern Integrated Optics ORION laser module with an IPG Photonics Erbium Fiber Laser to create an FCPDV. It was found that the 2 lasers used to create the FCPDV drifted from thermal influence (and the influence of their control systems to manage the thermal effects) in an unpredictable manner. A method was developed that uses back reflections of the main PDV laser from fiber optic junctions so that the effects could be measured, in situ, during dynamic measurements and be compensated for in postprocessing analysis. The methodology was employed while measuring the velocity of a speaker cone resonating at 100 Hz but more generally demonstrates the methodology toward how the US Army Research Laboratory's scientists could use FCPDV to eliminate the directional ambiguity associated with measurements of oscillating surfaces, such as a vehicle hull subjected to an under-body blast, or a reactive armor tile subject to nearest neighbor detonation.

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